UCRL-CONF-205148

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July 9, 2004

Materials Science and Technology 2004
New Orleans, LA, United States
September 26, 2004 through September 29, 2004

Plastic Deformation and Fracture of Steels under Dynamic Biaxial Loading

C.K. Syn[1]; J.C. Moreno[1]; D.M. Goto[1]; J.F. Belak[1]; D.E. Grady[2]

[1]Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94551, USA
[2]Applied Research Associates, 4300 San Mateo Blvd NE, Albuquerque, NM 87110, USA

Key words: Dynamic Biaxial Loading, Modeling, AerMet 100, Spall, Gas Gun

Abstract

Dynamic equi-biaxial bulging of thin AerMet 100 alloy plates was studied. The plates were deformed using a gas-gun driven flyer plate test set-up at impact velocities between 1.0 and 2.0 km/sec. The results indicate that in addition to biaxial stretching (and thinning) of the plate, internal cavitation (spallation fracture) results from the complex wave interactions within the plate. No outward evidence of damage was observed at the lower velocities, in the range of 1.0-1.2 km/sec. Fine scale cracking of the plates was observed at impact velocity above approximately 1.4 km/sec. Complete specimen fracture, in the form of multiple petals and pie-shaped fragments, was observed at impact velocity above 1.6 km/sec. Hydrodynamic computer code simulations were performed, prior to and in conjunction with the experiments, to aid in experiment design and interpretation of the experimental data.

Introduction

Study of plastic deformation and fracture behavior of metals at high strain rates is important in understanding and controlling of metal-forming process and failure behavior of engineering parts under dynamic loading conditions. Existing techniques for such studies include dynamic punch tests and other pressurized gas- or explosive-driven impact tests. In the present study, we introduce a novel idea of dynamic bulge testing in order to determine the failure strains in ductile materials under an equi-biaxial dynamic loading condition. The concept is shown schematically in Figure 1. A flyer plate, accelerated by a gas gun, impacts a buffer plate at a velocity *V*. The impact generates a shock in the buffer. The shock travels through the buffer and is transmitted into the target plate. The shock and corresponding momentum that is transmitted into the target causes the thin plate to deform under dynamic equi-biaxial tensile loading conditions. Also since the target plate is very weakly bonded to the buffer, deformation of the target plate is unimpeded by the buffer plate. To minimize the possibility of the cavitation inside the target plate, the thickness of the flyer plate was chosen to be slightly thinner than the flyer plate. This concept and experimental design was confirmed using hydrodynamic computer code calculations. The present paper describes and discusses some preliminary results.

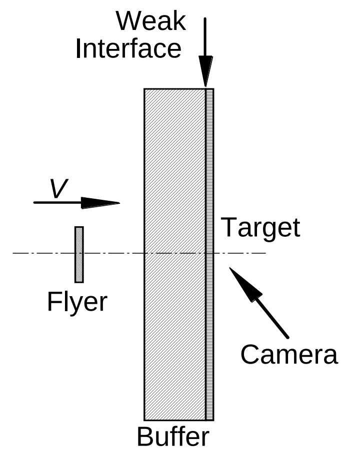


Figure 1: Schematics of dynamic bulge test. A flyer impacting the buffer at a velocity *V* generates a shock wave, which transmits to the target. The weakly bonded target bulges under a dynamic equi-biaxial loading condition.

Experimental Details

AerMet 100® alloy was selected as the material to study the dynamic biaxial deformation and fracture response. The material was procured from Carpenter Technology Corporation in the form of round stock of 152-mm diameter. The nominal composition of the material is 0.23%C, 3.1% Cr, 11.1% Ni, 1.2%Mo, 13.4% Co by weight and balance Fe [1]. The AerMet 100 was machined into thin, flat, round disk targets, approximately 152 mm (6 inch) in diameter and 3 mm in thickness. AerMet 100 targets were tested in the as-received, unhardened condition (approximately HRC 36); a set of AerMet 100 targets were also heat-treated, as per a procedure suggested by the supplier [1], to approximately HRC 53, but the results were not available for inclusion in this manuscript. Prior to testing, both surfaces of the targets were gridded by drawing two perpendicular sets of parallel lines spaced at 6.65mm (1/4 inch) or 2.54mm (1/10 inch) interval using a fine point permanent marking pen. The line thickness was about 1/5 mm. The grid patterns were later used to measure the local surface deformation strains, and were measured roughly center-to-center, with respect to the line thickness.

AerMet 100 target was attached to an OFHC copper plate (buffer) (200 mm x 200 mm x 25 mm) using nylon screws; see Figure 2(a). This assembly was attached to a lucite fixture, which included two laser timing pins and optical fibers to determine the flyer plate velocity (impact velocity). The target-buffer-lucite assembly was in turn mounted inside a target chamber, which facilitated soft-capture of the target plate or the use of real-time diagnostics (VISAR, high speed optical cameras) to measure the bulk target plate response. Figure 2 illustrates the experimental set-up. A 25-mm diameter, 3.3-mm thick cylindrical OFHC copper flyer, mounted in a lexan sabot, was used to impact the copper buffer. This impact imposes the conditions necessary to biaxially bulge the target plate.

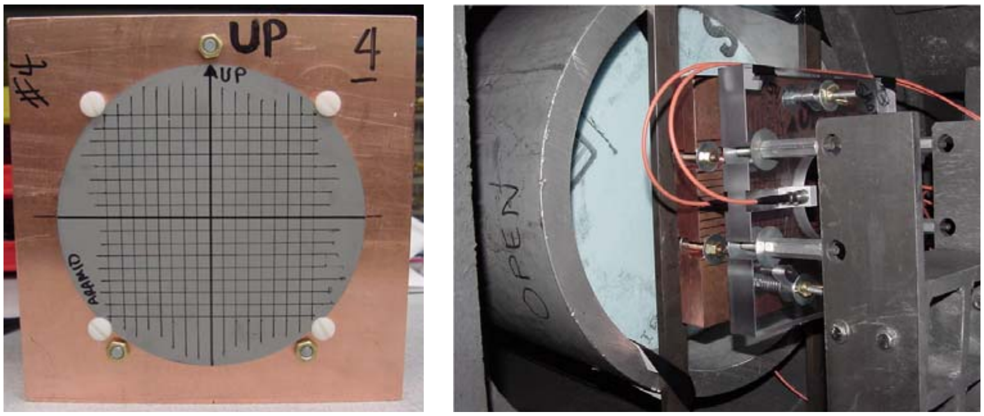


Figure 2: Target – buffer assembly. (a) Target is attached to buffer using four nylon screws. (b) A lucite plate containing laser velocity pins and fiber optics lines is attached to the target-buffer assembly. Behind the buffer is seen the recovery tube stuffed with foam.

The majority of tests were performed in order to recover the bulged target plate. Recovered targets were shown to have developed a dome-shaped bulge. Some targets were fractured in several pieces or opened up in multiple petals. Recovered targets were measured for deformed profiles by using laser profilometry or a 3-D coordinate measuring machine. Some targets had applied to them, prior to testing, a random speckle pattern. This pattern was photographed prior to impact testing and subsequently re-photographed, post-shot, and a 3-D photogrammetric image correlation technique [2] was applied to determine the in-plane (surface) deformation. A subset of tests was performed using high-speed framing cameras and/or VISAR diagnostics [3]. These data were compared with computer code simulations.

Computer code simulations were performed using the 2-D arbitrary Lagrange-Eulerian multi-material, hydrodynamic code, CALE [4, 5]. The Steinberg-Guinan strength model, coupled with an analytic Gruneisen equation of state model, was used to model all materials in the experiment [6]. A rudimentary criterion for ductile fracture, based on strain and minimum pressure (maximum tension), was also utilized. Calculations were run *Lagrangian* as much as possible. Some regions (mostly the flyer-buffer interface) were allowed to advect and contain mixed zones in order for the problem to run smoothly. Typical zone sizes for these calculations are around 0.20 mm.

Results and Discussion

Table 1 lists the results of dynamic impact (dynamic bulge) experiments. Testing was performed to study the biaxial deformation behavior of thin plates, encompassing bulging/deforming/damaging the material, to forming incipient cracks, to fracturing the material. Characteristic examples of bulged and fractured specimens are illustrated in Figures 3 and 4.

Table 1: List of impact shots

Target Material	Flyer Velocity, km/s	Comment
Unhardened AerMet 100, Flat, 6"D, 1/8"T	1.06	Bulged
	1.15	Bulged
	1.40	Bulged
	1.55	Fine-scale cracking on top and bottom surfaces
	1.60	Fractured (6 petals)

Un-hardened AerMet 100 (HRC 36) targets impacted at 1.55 km/sec and 1.60 km/sec show markedly different responses, as shown in Figure 3; a small increase in velocity results in catastrophic material failure. Specimens that deformed but did not fracture, possess bulges that are approximately centered with respect to the target plate. In specimens where the bulge is slightly off-centered with respect to the center of the target, the bulge is symmetric with respect to its apex. In other words, the bulge height and, therefore, the material deformation are symmetric about the apex of the bulge; see Figure 4.

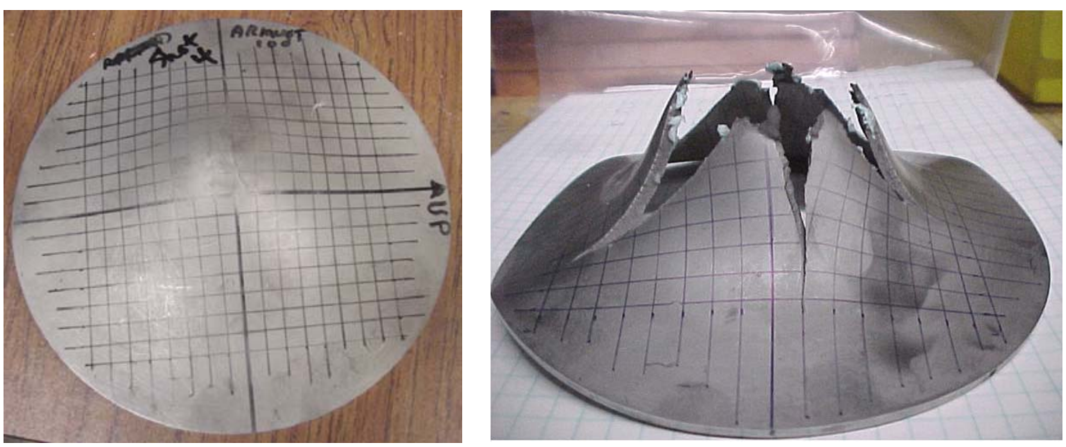


Figure 3: Examples of flat, unhardened (HRC 36) AerMet 100 targets dynamically bulged at flyer plate impact velocities of (a) 1.55 km/sec and (b) 1.60 km/sec.

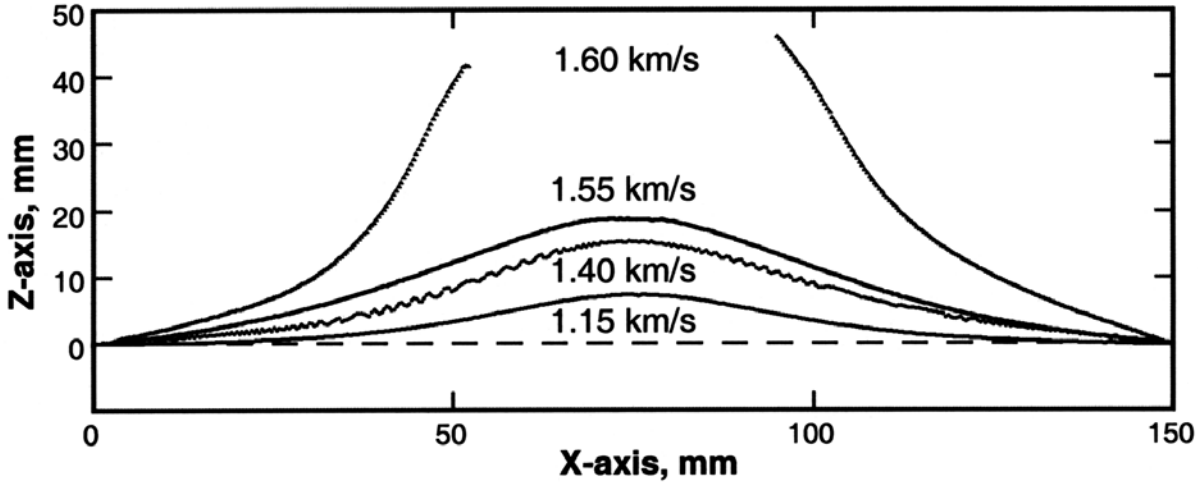
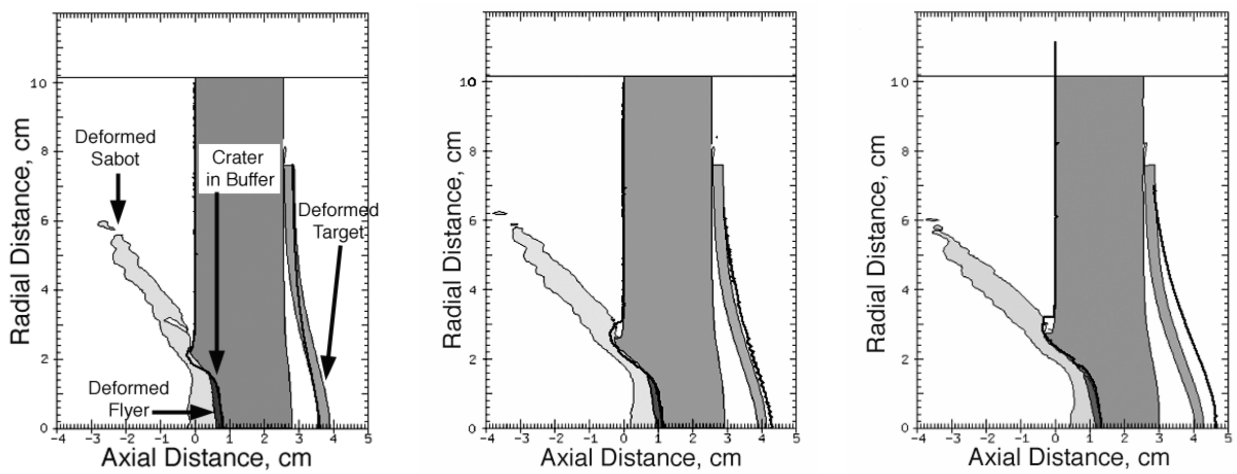


Figure 4: Profiles of unhardened AerMet 100 targets impacted at flyer velocities indicated next to each profile

Shown in Figure 5 are three snapshots at 60 μsec after impact for flyer impact velocities of 1.15, 1.40, and 1.55 km/sec. Measured (solid thicker lines) and computed profiles (filled plot) of the copper buffer (flyer plate impact side) and those of the un-hardened AerMet 100 target on the top (or outer) surface are compared in Figure 5. The hydrodynamic computer code (CALE) results are in rather good agreement with the post-test measured profiles, considering the material strength model employed, *i.e.*, Steinberg-Guinan, does not incorporate temperature or rate-dependency within its framework. Best agreement between experiment and simulation is achieved for the 1.40 km/sec condition, whereas the agreement degrades at 1.15 km/sec and 1.55 km/sec conditions.

The disparity between computation and experiment for the 1.15 km/sec condition is manifested by the larger extent of deformation, computed, in comparison to the experiment; see Figure 5(a). This result tends to suggest that the strength model representation of un-hardened AerMet 100 is, for a lack of a better description, too soft. In contrast, the disparity between computation and experiment for the 1.55 km/sec condition suggests the strength model characterization is too hard; see Figure 5(c). This latter situation shows a measured profile, *i.e.*, bulge, that is larger than that computed. The lack of an explicit temperature and strain-rate dependency in the Steinberg-Guinan model may in part account for the discrepancy between computations and experiments, however, the exact nature is not known.

Specimens impacted at velocities less than approximately 1.40 km/sec displayed no obvious signs of cracking or fracture. Inspection of fractured specimens, *i.e.*, *petalled* specimens, revealed inclined fracture surfaces (often referred to as shear fracture surfaces). Due to the apparent extent of plastic deformation involved in the fracture process, we presume the fracture is ductile; however, no detailed fractographic analysis was performed to confirm the presence of a characteristic dimpled fracture surface. Several specimens showed evidence of cracking (incipient failure) on both the top (free surface) and bottom (surface in contact with the copper buffer) surfaces. An example of these surface cracks on the top and bottom surface of an un-hardened AerMet 100 target impacted at 1.55 km/sec is illustrated in Figure 6. These cracks precede plate failure, *i.e.*, *petalling*, and may be interpreted as the onset of material failure.



(a) V=1.15 km/sec (b) V=1.40 km/sec (c) V=1.55 km/sec

Figure 5: Comparison of the target, buffer and flyer profiles at 60 μsec after impact at three different flyer velocities, (a) 1.15, (b) 1.40 and (c) 1.55 km/sec, respectively with the CALE-simulated profiles. The solid black lines in each figure represent the profiles of copper buffer on the impact side and the top (or outer) surface of the target.

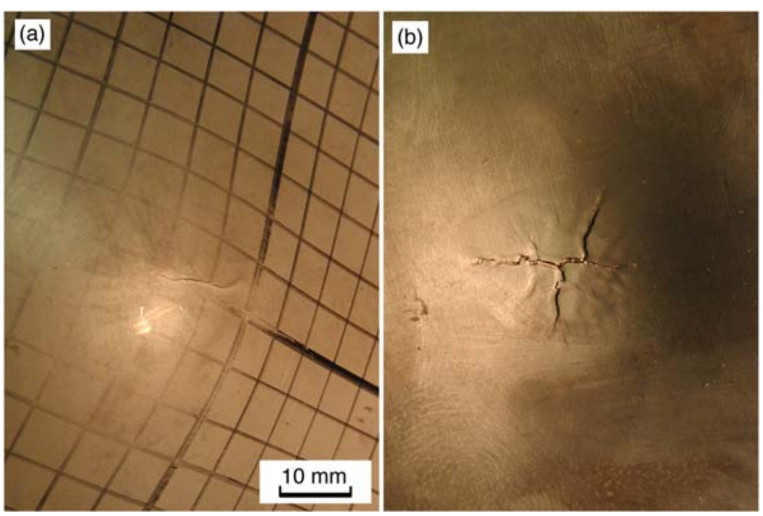


Figure 6: Fine–scale incipient cracks observed in un-hardened AerMet 100 target impacted at 1.55 km/sec. The image in (a) shows the crack on the top surface and the image in (b) shows the crack on the bottom or under-surface. The range of the incipient cracks showing the surface relief effect is estimated to be about 25 mm (1 inch).

In-plane (top surface of the target plate) strain estimations, made by measuring gridline separations and utilizing photogrammetric techniques, indicated strain levels of approximately 0.09 – 0.11 in the apex region of the bulge, depending on impact velocity. In other words, the un-hardened AerMet 100 target impacted at 1.0 km/sec stretched approximately 0.09, whereas the target impacted at 1.55 km/sec stretched approximately 0.11. No strain measurements were made yet on other targets. Measurements made in the orthogonal direction indicated a similar level of strain (0.09 – 0.11) and suggested deformation of the material was isotropic. Thickness measurements in the domed region of the un-hardened AerMet100 target impacted at 1.55 km/sec indicated a corresponding through-thickness strain of approximately -0.16 in the apex region of the bulge. Readily evident is the apparent violation of conservation of volume in the AerMet 100 target impacted at 1.55 km/sec; i.e., $-(0.11 + 0.11) \neq -0.16$. The origin of this discrepancy may be the result of dilation of the target in the thickness direction, due to internal cavitation (spall), observed within the target material.

Cross-sectional metallography of the unhardened AerMet100 target impacted at 1.55 km/sec clearly revealed internal cavitation within the material; see Figure 7. Unlike traditionally spalled flyer-plate targets, where the spall plane is centered within the target, the current spall-plane is located near the buffer-target interface (rear surface of the target plate). The region of internal cavitation extended approximately 25 mm (~1.0 inch) in diameter. The presence of this cavitation (or spall) plane clearly gives rise to an apparent thickening of the target plate. The degree of thickening is roughly equal to added thickness of the target plate due to the porosity. Subtracting the porosity-thickness from the overall target plate thickness, and calculating a porosity-compensated thickness strain, a strain value of roughly – 0.25 is obtained. Albeit this value does not agree, exactly with that expected based on the in-plane surface strain estimation, it is an improvement over the earlier estimating based on the overall target plate thickness, and is probably well within the experimental error characterizing the measuring methods.

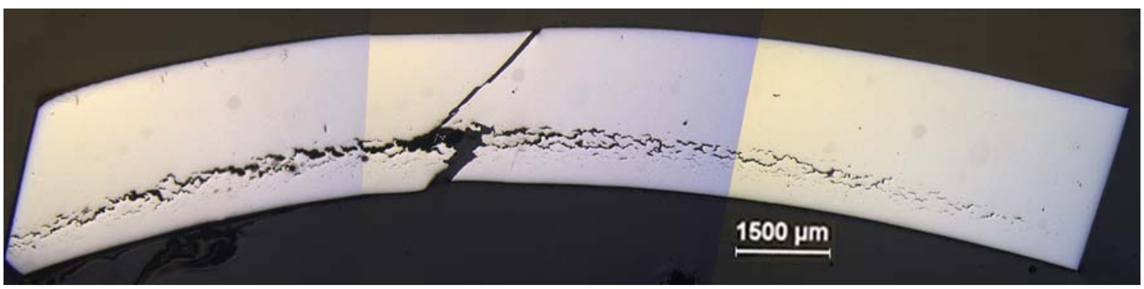


Figure 7: Cross-sectional micrograph of internal crack and pores developed in an un-hardened AerMet 100 target impacted at 1.55km/sec shown in Figure 6.

CALE calculations revealed that complex wave interactions within the target plate during the bulging process, can create high tensile stresses within the material, in a region 0.50 to 1.5 mm from the rear surface of the target plate. Tensile stresses on the order of 1 to 3 GPa are estimated within the observed cavitation range. Based on this calculated stress range, our results suggest the spall strength of un-hardened AerMet is on the order of 1 GPa, which is less than the 5.3 GPa recorded for *as-received* AerMet-100 by Reinhart et al. from their 1-D flyer plate experiment [7].

Also evident in Figure 7 are inclined cracks that intersect either (inner or outer) surface of the target and both intersect the spall plane. The presence of inclined cracks may be expected considering the imposed biaxial stress-state and the tendency of thin plate material to exhibit localized shear deformation in the through-thickness direction. The nature and origin of the inclined cracking, however, was not investigated in detail. The dog-leg shaped kinking of the inclined crack at the spall plane suggests the spall plane was formed, initially, followed by the formation of the inclined crack.

Concluding Remarks

A series of dynamic equi-biaxial bulging experiments were performed to study the deformation and fracture behavior of AerMet 100 alloy. A gas-gun driven flyer plate impacted thin plates of AerMet 100 alloy at velocities between 1.0 and 2.0 km/sec, imparting stresses sufficient to bulge, crack, and fracture the alloy. Shear (inclined) cracks were observed in targets impacted at the highest velocities (> 1.5 km/sec). Internal cavitation of the alloy was also observed and was manifested in terms of the post-test plate thicknesses larger than expected. In the presence of internal cavitation, the shear cracks observed (in cross-section) appeared to intersect the spall plane, giving rise to an appearance of *crack kinking*. Equivalent plastic strain to failure was estimated as 0.16 - 0.19, assuming conservation of volume and the in-plane strain of 0.11 or through-thickness strain of 0.25.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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